Survival of Adult *Tiphia vernalis* (Hymenoptera: Tiphiidae) After Insecticide, Fungicide, and Herbicide Exposure in Laboratory Bioassays

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ABSTRACT *Tiphia vernalis* Rohwer is a hymenopteran ectoparasitoid of Japanese beetle, *Popillia japonica* Newman, larvae. The adult wasps feed on nectar or honeydew between mid-April and late June. Adults may contact pesticides when landing on foliage or when females hunt for grubs in the soil. The lethal effect of nursery, turf, and landscape pesticides was determined by exposing wasps to treated foliage in the laboratory. Pesticides tested at labeled rates were the insecticides bifenthrin, carbaryl, chlorpyrifos, halofenozide, and imidacloprid; the herbicides oryzalin, pendimethalin, and a combination product with 2,4-D, dicamba, and mecoprop (multiherbicide); and the fungicides chlorothalonil and thiophanate-methyl. During 2001 and 2002, male and female *T. vernalis* were exposed to pesticides by using turf cores. For both years, bifenthrin, chlorpyrifos, and imidacloprid treatments lowered adult survival relative to the control, but halofenozide had minimal effect on mortality of males and females. More males than females died after exposure to carbaryl treatments. Survival of females was not reduced by exposure to herbicides or fungicides. Females were apparently more tolerant of pesticides than males. Mortality of males in response to herbicides and fungicides was more variable than for females; in 2002 trials, male mortality was higher after exposure to multiherbicide, oryzalin, pendimethalin, and thiophanate-methyl than the control. The fungicide chlorothalonil did not increase mortality of males or females in either year. Sublethal effects were not evaluated. The study indicates the choice of pesticide may be important for conserving *T. vernalis* in nursery, landscape, and turf settings.

KEY WORDS *Tiphia vernalis*, fungicides, herbicides, insecticides, compatibility

The Japanese beetle, *Popillia japonica* Newman (Coleoptera: Scarabaeidae), was discovered in New Jersey in 1916 and has since expanded its range to most states bordering and east of the Mississippi River, where it has become a serious horticultural and turf pest as well as a regulatory issue for nursery stock shipments (Fleming 1972, Potter and Held 2002, USDA 2003). Research on the biological control of *P. japonica* began in the 1920s (Fleming 1968, 1976). *Tiphia vernalis* Rohwer (Hymenoptera: Tiphiidae) was one of the natural enemies released and established during this period. The wasp is a solitary parasitoid that attacks third instars of *P. japonica* and oriental beetle, *Anomala orientalis* Waterhouse (King et al. 1951; Reding and Klein 2001; M.G.K., unpublished data). *T. vernalis* was originally released in many of the northeastern states as well as midwestern states such as Ohio, and southern states such as Virginia and North Carolina (King et al. 1951). Current populations of *T. vernalis* are documented in Kentucky, Ohio, and Tennessee (Reding and Klein 2001, Rogers and Potter 2004c, Oliver et al. 2005).

The seasonal life history of *T. vernalis* has edaphic and arboreal periods. The adult parasitoid emerges from early April to early June depending on location, with males generally emerging before females (Rogers and Potter 2004b; J.B.O. and M.G.K., unpublished data). The wasps feed on honeydew or nectar and can be attracted by spraying solutions of sugar water on foliage (Gardner 1938, Gardner and Parker 1940, Rogers and Potter 2004c). Females typically hunt for grubs in the soil during the early afternoon (Gardner 1938). The female wasp locates a host grub by scent cues (Rogers and Potter 2003) and lays an egg externally in the ventral suture between the third thoracic and first abdominal segments (King and Parker 1950). The egg hatches in ≈1 wk, and the parasitoid larva feeds ex-

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ternally for ≈3 wk before consuming the host and forming a cocoon that will house the adult through the following winter (Gardner 1938, King and Parker 1950, Rogers and Potter 2003). The hunting and feeding activities of adult wasps and the larval developmental periods in the soil may expose *T. vernalis* to pesticides on soil and leaf surfaces (Tooker and Hanks 2000, Rogers and Potter 2004c).

The contribution of biological control agents to pest management can be disrupted by pesticide treatments. For example, *T. vernalis* may parasitize up to 60% of the larval *P. japonica* populations at a site with females laying 40–50 eggs in a lifetime (Gardner and Parker 1940, King and Parker 1950, Fleming 1976, Rogers and Potter 2004b). Few studies have assessed the impacts of pesticides on *Tiphia* wasps. It is likely that *T. vernalis* is exposed to herbicides, fungicides, and insecticides commonly used in commercial nurseries, turf farms, residential lawns, and golf courses during mid- to late spring (Watschke et al. 1994, Braman et al. 1997, Rogers and Potter 2004b). Most studies examining the interaction of *T. vernalis* with pesticides have tested imidacloprid, because of its persistence, widespread use for scarab management, and application time that overlaps with periods of *T. vernalis* flight activity (Kunkel et al. 1999; Rogers and Potter 2003, 2004a; Oliver et al. 2005). Imidacloprid had sublethal effects on *T. vernalis* reproduction when foliar applied to cores of turf and also reduced parasitism rates in the field (Rogers and Potter 2003). However, in a laboratory study where imidacloprid was soil incorporated, the insecticide had no significant effect on parasitism rate or ability of *T. vernalis* larvae to survive to the cocoon stage (Oliver et al. 2005). The effects on *T. vernalis* from other soil-incorporated insecticides tested by Oliver et al. (2005) ranged from minimal (halofenozide) to detrimental (carbaryl, chlorpyrifos, and thiamethoxam). No studies to date have examined the effect of herbicides and fungicides on *T. vernalis.* The objective of this study was to determine the effects of commonly used turf and ornamental pesticides on survival of adult *T. vernalis* under laboratory conditions.

Materials and Methods

Wasp Collection and Handling. Adult *T. vernalis* were field collected from a commercial nursery near Tarlton, TN (35° 30.652′ N 85° 40.570′ W). Wasps were attracted to an uncultivated field border consisting primarily of Japanese honeysuckle, *Lonicera japonica* Thunberg, by spraying a 10% (wt:vol) sugar water solution with a trigger operated Spraymaster Sm-87 pump sprayer (Delta Industries, Philadelphia, PA). Male wasps were collected between 10 and 27 April and female wasps between 27 April and 13 May, beginning with the first major appearance of each gender in the field. Wasps were typically collected over several days. Daily captures of wasps were combined in a 30- by 30- by 30-cm aluminum insect cage (BioQuip, Rancho Dominguez, CA) to mix wasp collections before use in experiments. The cage contained a 5-liter plastic pan filled with moistened sphagnum moss as a wasp harborage. Wasps were fed by providing a 2-cm piece of cotton dental wick saturated in 10% sugar water and held in a plastic weigh boat (4.1 by 4.1 cm by 8 mm in height). Wasps were shipped overnight express with sugar-saturated wicks in a 3.8-liter plastic container filled with moistened sphagnum moss to the USDA–ARS Application Technology Research Unit, Horticultural Insects Laboratory (Wooster, OH). In Ohio, wasps were held in the container for 1 to 2 d at 15°C before laboratory experiments.

Turf Core Pesticide Bioassays: 2001 and 2002. Cores of Kentucky bluegrass, *Poa pratensis* L., were taken with a 10-cm-diameter golf course cup cutter from an untreated turf plot 1 d before the test. In the laboratory, each core was fitted into an 11.5-cm-diameter by 7.5-cm-deep plastic cup (Sweetheart Plastics Inc., Chicago, IL). Cores received 30-ml of water to maintain moisture. The next day, the cores were removed from the cups and the grass blades were sprayed to runoff with various pesticides (characterized in Table 1 and listed in Table 2). In 2002, Lesco 3-Way Selective Herbicide was substituted for Trimec Classic used in 2001. Both Lesco 3-Way Selective and Trimec Classic contain 2,4-D, mecoprop (MCPP), and dicamba in proportions of 30.6, 8.2, and 2.8% and 25.9, 6.9, and 2.8%, respectively, and are hereafter referred to as multiherbicide. In 2002, Dursban TNP (41.2% chlorpyrifos) and Sevin SL (43.0% carbaryl) were substituted for Dursban 4E (44.8% chlorpyrifos) and Sevin XLR (41.2% carbaryl) used in 2001. Dursban and Sevin formulations are hereafter referred to as chlorpyrifos and carbaryl. Cores were placed back in cups and allowed to surface dry. During 2001 and 2002, each pesticide treatment was replicated three times with either five males or five females per core in a completely randomized design for a total of 15 male and 15 female wasps per treatment. Wasps were fed during bioassays as described previously. During 2001, plastic lids without air exchange holes were placed on cups. In 2002, cup lids had an 18 by 22 mesh screen glued over a 2.5- by 2.5-cm opening to improve air exchange. All containers were held on a laboratory bench at 21–27°C under a photoperiod of 9:15 (L:D) h. Data for mortality were analyzed by analysis of variance (ANOVA) after transforming the percentage of dead adults by arcsine (square root [X]). The least significant difference test was used to separate means ($\alpha = 0.05$) (SAS Institute 1996).

Results

Turf Core Pesticide Bioassays: 2001 and 2002. In 2001, mortality of male *T. vernalis* exposed to bifenthrin, carbaryl, chlorpyrifos, and imidacloprid treatments was higher than the control at 24 h ($F = 7.74$; df = 10, 22; $P < 0.0001$) and 48 h ($F = 7.71$; df = 10, 22; $P < 0.0001$) (Table 2). At 48 h, mortality in the bifenthrin, carbaryl, chlorpyrifos, and imidacloprid treatments was also higher than the other noncontrol treatments. Mortality in the halofenozide, herbicide,

Table 1. Insecticides, herbicides, and fungicides used in all experiments, including chemical and trade names, formulations, manufacturers, and rates based on labeled amount of active ingredient

Pesticide type	Chemical name	Trade name[a]	Formulation	Manufacturer[b]	Rate	
					g or ml product/liter	kg (AI)/ha
Insecticide	Bifenthrin	Talstar F insecticide/miticide	F	FMC	2.98	0.22
	Carbaryl	Sevin	XLR	Rhone-Poulenc	20.00	8.96
	Carbaryl	Sevin	SL	Bayer	20.00	8.96
	Chlorpyrifos	Dursban	4E	Dow	5.00	2.24
	Chlorpyrifos	Dursban	TNP	Verdicon	5.00	2.24
	Halofenozide	Mach2	F	Dow	10.00	2.24
	Imidacloprid	Merit	75 WP	Bayer	0.64	0.45
Fungicide	Chlorothalonil	Daconil Ultrex	WDG	Syngenta	1.67	1.30
	Thiophanate-methyl	Cleary's 3336	F	Cleary	34.00	17.14
Herbicide	2,4-D, Dicamba, and MCPP	3-Way Selective	EC	Lesco	5.00	1.14, 0.12, 0.70
	2,4-D, Dicamba, and MCPP	Trimec Classic	EC	PBI-Gordon	5.00	1.14, 0.12, 0.61
	Oryzalin	Surflan	A.S.	Dow	5.00	2.24
	Pendimethalin	Lesco Pre-M Turf	3.3 EC	Lesco	4.50	1.68

[a] Dursban 4E and Sevin XLR were used in 2001 tests, and Dursban TNP and Sevin SL were used in 2002 tests. Trimec was used in 2001 tests, and Lesco 3-Way Selective Herbicide was used in 2002 tests.

[b] FMC, FMC Corporation, Philadelphia, PA; Rhone-Poulenc, Rhone-Poulenc Ag Company, Research Triangle Park, NC (company does not currently exist); Bayer, Bayer Corporation, Kansas City, MO; Verdicon, Verdicon, Greeley, CO; Dow, Dow AgroSciences LLC, Indianapolis, IN; Syngenta, Syngenta Crop Protection, Inc., Greensboro, NC; Cleary, Cleary Chemical Corporation, Dayton, NJ; Lesco, Lesco, Inc., Strongsville, OH; and PBI-Gordon, PBI-Gordon Corp., Kansas City, MO.

or fungicide treatments was not higher than the control at 24 and 48 h.

In 2002, mortality of male *T. vernalis* exposed to bifenthrin, carbaryl, chlorpyrifos, and imidacloprid was higher than other treatments at both 24 h ($F = 47.89$; df = 10, 22; $P < 0.0001$) and 48 h ($F = 26.48$; df = 10, 22; $P < 0.0001$) (Table 2). Relative to the control treatment, mortality of male wasps was also higher in the pendimethalin and multiherbicide treatments at both evaluation times and in the oryzalin and thiophanate-methyl treatment at 48 h. Unlike in 2001, no mortality occurred in the control treatment in 2002, which may have contributed to more pesticide treatments differing from the control in 2002.

In 2001, mortality of female *T. vernalis* exposed to chlorpyrifos, imidacloprid, and bifenthrin was higher than other treatments at 24 h ($F = 22.27$; df = 10, 22; $P < 0.0001$) and 48 h ($F = 25.31$; df = 10, 22; $P < 0.0001$)

Table 2. Mean ± SE number of dead adult male and female *T. vernalis* after 24- and 48-h exposure to insecticide-, herbicide-, and fungicide-treated Kentucky bluegrass cores of turf in 2001 and 2002

Gender	Treatment[a]	Chemical group	n[b]	2001[c]		2002[c]	
				24 h	48 h	24 h	48 h
Male	Untreated		3	0.7 ± 0.7ab	2.3 ± 1.3abc	0.0 ± 0.0a	0.0 ± 0.0a
	Chlorothalonil	Fungicide	3	0.0 ± 0.0a	1.3 ± 0.3abc	0.0 ± 0.0a	0.3 ± 0.3ab
	Oryzalin	Herbicide	3	0.3 ± 0.3ab	1.0 ± 0.6a	0.3 ± 0.3a	1.3 ± 0.9bc
	Thiophanate-methyl	Fungicide	3	0.3 ± 0.3ab	1.0 ± 0.0ab	0.3 ± 0.3a	1.3 ± 0.3cd
	Halofenozide	Insecticide	3	0.7 ± 0.7ab	1.3 ± 0.3abc	0.3 ± 0.3a	0.7 ± 0.3abc
	Pendimethalin	Herbicide	3	2.0 ± 0.6bc	3.0 ± 1.0bc	1.7 ± 0.3b	3.3 ± 0.3e
	Multiherbicide	Herbicide	3	2.0 ± 1.5bc	3.3 ± 0.9c	2.7 ± 0.9b	2.7 ± 0.9de
	Carbaryl	Insecticide	3	4.0 ± 0.7de	5.0 ± 0.0d	5.0 ± 0.0c	5.0 ± 0.0f
	Imidacloprid	Insecticide	3	4.7 ± 0.3de	5.0 ± 0.0d	5.0 ± 0.0c	5.0 ± 0.0f
	Bifenthrin	Insecticide	3	3.3 ± 0.3cd	5.0 ± 0.0d	5.0 ± 0.0c	5.0 ± 0.0f
	Chlorpyrifos	Insecticide	3	5.0 ± 0.0e	5.0 ± 0.0d	5.0 ± 0.0c	5.0 ± 0.0f
Female	Untreated		3	0.7 ± 0.3ab	1.0 ± 0.6b	0.3 ± 0.3ab	1.0 ± 0.6ab
	Chlorothalonil	Fungicide	3	0.0 ± 0.0a	0.0 ± 0.0a	0.0 ± 0.0a	0.7 ± 0.7a
	Oryzalin	Herbicide	3	0.0 ± 0.0a	0.3 ± 0.3ab	0.7 ± 0.7ab	0.7 ± 0.7a
	Thiophanate-methyl	Fungicide	3	0.0 ± 0.0a	0.0 ± 0.0a	0.7 ± 0.3ab	1.7 ± 0.3ab
	Halofenozide	Insecticide	3	0.0 ± 0.0a	0.3 ± 0.3ab	0.3 ± 0.3ab	1.0 ± 0.6ab
	Pendimethalin	Herbicide	3	0.3 ± 0.3a	0.3 ± 0.3ab	0.3 ± 0.3ab	1.0 ± 0.0ab
	Multiherbicide	Herbicide	3	0.7 ± 0.3ab	1.0 ± 0.0bc	1.3 ± 0.3b	2.0 ± 0.0b
	Carbaryl	Insecticide	3	1.3 ± 0.3b	2.3 ± 0.9c	1.0 ± 0.6ab	1.3 ± 0.9ab
	Imidacloprid	Insecticide	3	4.3 ± 0.8c	4.7 ± 0.3d	4.7 ± 0.3c	5.0 ± 0.0c
	Bifenthrin	Insecticide	3	4.7 ± 0.3c	5.0 ± 0.0d	5.0 ± 0.0c	5.0 ± 0.0c
	Chlorpyrifos	Insecticide	3	4.7 ± 0.3c	5.0 ± 0.0d	5.0 ± 0.0c	5.0 ± 0.0c

Means within a column followed by a different letter were significantly different ($P < 0.05$) as indicated by analysis of variance on percentage of dead adults after transformation by arcsine (square root [X]) with means separated by least significant difference test.

[a] See Table 1 for complete description of insecticide names and rates.

[b] Five male and five female wasps were used per replicate (i.e., total of 15 males and 15 females per treatment, respectively).

[c] Averages are numbers of wasps killed among five adults/3.

(Table 2). At 24 h, mortality of females in carbaryl, halofenozide, and the fungicide and herbicide treatments was equivalent to the control. At 48 h, mortality of females in the carbaryl treatment was higher than the control, but halofenozide and herbicide and fungicide treatments remained equivalent to the control. Mortality of females in the chlorothalonil and thiophanate-methyl treatments was significantly lower than the control at 48 h.

In 2002, female *T. vernalis* exposed to chlorpyrifos, imidacloprid, and bifenthrin had higher mortality than other treatments at 24 h ($F = 19.10$; df = 10, 22; $P < 0.0001$) and 48 h ($F = 12.99$; df = 10, 22; $P < 0.0001$) (Table 2). Mortality in the herbicide, fungicide, carbaryl, and halofenozide treatments did not differ from the control at 24 and 48 h. The multiherbicide treatment had higher female mortality than oryzalin at 48 h and chlorothalonil at 24 and 48 h.

Discussion

The current study found some pesticides are detrimental to *T. vernalis* adults when applied to cores of turf. The insecticides bifenthrin, carbaryl, chlorpyrifos, and imidacloprid were toxic to male and female *T. vernalis* when applied to cores. However, female *T. vernalis* exhibited less toxicity than males to insecticides such as carbaryl and halofenozide. Among insecticides tested, halofenozide was the least toxic to *T. vernalis.* The chemical properties and mode of action of insecticides are important determinants of toxicity to different insect taxonomic groupings or life stages such as larvae, pupae, and adults. Imidacloprid and halofenozide are reported to have more selectivity in their activity toward beneficial insects (Dhadialla et al. 1998, Cowles et al. 1999, Kunkel et al. 1999). Halofenozide has an ecdysteroid agonist mode of action that targets the molting process of larvae, which may explain the minimal effects observed on adult *T. vernalis* (Dhadialla et al. 1998). In contrast, the other insecticides tested are neurotoxic, which could increase toxicity for either adults or larval insects. The negative effects of organophosphate, carbamate, and pyrethroid insecticides on beneficial insects are well documented (Arnold and Potter 1987, Theiling and Croft 1988, Terry et al. 1993, Bradley 1999, Vittum et al. 1999, Gels et al. 2002). Field and laboratory studies with imidacloprid have found detrimental effects on beneficial insects such as carabids, chrysopids, coccinellids, histerids, mirids, staphylinids, and bumblebees, but in some cases the effects were short lived or reduced with posttreatment irrigation (Mizell and Sconyers 1992, Kunkel et al. 1999, Gels et al. 2002). In addition, imidacloprid-treated turf decreased parasitism of *P. japonica* larvae by intoxicating *T. vernalis* and altering their host-finding and -parasitizing behavior (Rogers and Potter 2003). Most of the insecticides tested are persistent in the soil or on foliar surfaces with half-live ranges for chlorpyrifos, carbaryl, bifenthrin, and imidacloprid at 6–139, 3–110, 7–240, and 61–150 d, respectively, increasing the exposure potential for *T. vernalis* in the field (Montgomery 1997, Vittum et al. 1999, Extoxnet PIP 2005).

In general, fungicides and herbicides were less toxic to *T. vernalis* than insecticides. Among fungicides and herbicides tested, multiherbicide, oryzalin, pendimethalin, and thiophanate-methyl only increased mortality of male wasps during 2002 testing. Herbicides and fungicides had no measured impact on the mortality of females. For chlorothalonil, mortality of male and female wasps was equivalent to or less than the control in all tests. Female wasps were apparently more tolerant of pesticides than male wasps. The 2,4-D portion of 3-Way and Trimec Classic is reported to be toxic to bees as well as aquatic insects (WSSA 1994, Extoxnet PIP 2005), which supports the lower male survival observed in this study. Chlorothalonil and thiophanate-methyl are toxic to aquatic invertebrates (MacKay et al. 1997, Extoxnet PIP 2005), but they did not significantly increase *T. vernalis* mortality. Most of the herbicides and fungicides tested can persist on foliage and potentially expose *T. vernalis* adults to posttreatment residues (MacKay et al. 1997, Montgomery 1997, Extoxnet PIP 2005). Dinitroanaline herbicides such as oryzalin and pendimethalin are volatile, which could increase insect exposure to volatiles but would also lower residues on treated surfaces. Dicamba and 2,4-D are absorbed rapidly into foliage, which may lower residue exposures to *T. vernalis* (WSSA 1994, Extoxnet PIP 2005).

In our study, *T. vernalis* adults were placed on treated foliage shortly after it had air-dried. The short interval between foliage treatment and adult introduction may have exposed wasps to higher pesticide levels than normally found in the field environment. Under field conditions, pesticide dissipation is influenced by factors such as the substrate treated, the chemical and physical properties of the pesticide, and environmental conditions such as rainfall, temperature, and solar incidence (Montgomery 1997, Vittum et al. 1999). Laboratory conditions eliminated or reduced some dissipation factors such as rainfall and photolytic depletion. However, during the course of the 48-h experiments, it is likely that some pesticides dissipated more rapidly because of differences in the physical–chemical properties of the pesticide. Pesticides that dissipate quickly by vaporizing would reduce residues on foliage and thatch, but they also could be more toxic to *T. vernalis* adults by fumigant action (Harris 1982, Elliott 1988). Pesticide vapor pressure, whether high (e.g., 0.9–1.3 mmHg $\times 10^{-4}$ at 20–25°C; carbaryl and chlorpyrifos), moderate (0.0017–0.0057; multiherbicide, halofenozide, and chlorothalonil), or low (0.0000001–0.000712; oryzalin, imidacloprid, pendimethalin, and thiophanate-methyl), did not seem to be a good predictor of whether a pesticide would be toxic to *T. vernalis* (MacKay et al. 1997, Montgomery 1997, Vittum et al. 1999, TOR 2005).

In addition to the amount of pesticide residue on the leaf, a more important determinant of *T. vernalis* exposure and subsequent mortality may be the amount of residue that dislodges from the treated substrate. The toxicity of insecticides to other hymenopterans such as honey bees and a solitary parasitic wasp was directly proportional to the amount of dislodged residues (Bellows et al. 1993, Chukwudebe et al. 1997). The substrate surface and the type of pesticide can alter the amount of dislodgeable residue (Antonious and Snyder 1995, Chukwudebe et al. 1997). Preliminary tests using maple leaves suggest insecticides such as halofenozide may be more toxic to *T. vernalis* on maple leaf surfaces than the turf cores used in this study (J.B.O. and M.E.R., unpublished data). In turf settings, residues of fungicides, herbicides, and insecticides may remain for weeks to months in the thatch zone because of strong adsorption with thatch and leaves (Niemczyk and Krueger 1987, Lickfeldt and Branham 1995). For example, 92% of chlorpyrifos residues were recovered from thatch on the day of application despite posttreatment irrigation (Sears and Chapman 1979). Insecticides that strongly adsorb to soil are less toxic to insects, which also may relate to pesticides applied to thatch (Harris 1982). The mortality exhibited by *T. vernalis* to chlorpyrifos and some of the other pesticide treatments in this study, suggests residues on the treated cores were both sufficiently concentrated and dislodgeable to induce wasp toxicity. In another laboratory study, soil incorporated imidacloprid, halofenozide, and thiamethoxam did not reduce the ability of *T. vernalis* to find and parasitize *P. japonica* larvae, and imidacloprid and halofenozide did not prevent the parasitoid larvae from developing to the cocoon stage (Oliver et al. 2005). It is probable the amount of dislodgeable residue varies between soil, thatch, and foliar substrates because of differences in pesticide adsorption to these surfaces (Harris 1982).

In conclusion, our laboratory study indicates that exposure of adult *T. vernalis* to some pesticide residues on nonirrigated plant foliage may kill the wasps. Therefore, methods that reduce pesticide residues on leaf surfaces such as posttreatment irrigation or subsurface pesticide placement, when compatible with the requirements for effective pest control, may enhance conservation of *T. vernalis.* The pesticides tested are all applied occasionally to commonly in the landscape, nursery, and turf industries during the *T. vernalis* flight interval (Watschke et al. 1994, Garber and Hudson 1996, Braman et al. 1997, Mannion et al. 2001, TOR 2005), which occurs from mid-April to late June depending on geographic location (Rogers and Potter 2004b; J.B.O. and M.G.K., unpublished data). Chlorpyrifos is no longer permitted in residential or landscape settings where children may be exposed, but it can be used in agricultural, golf course, road medians, and industrial sites where exposure to *T. vernalis* may be substantial (USEPA 2000). If applications can be made before or after the primary *T. vernalis* flight period, then impacts on these beneficial wasps may be reduced. Female wasps typically occur later in the field season than males and were less susceptible to pesticide treatments. Therefore, spray treatments applied during May and June may not impact *T. vernalis* populations if the majority of the females have mated. As expected, most herbicides and fungicides had less effect on *T. vernalis* mortality than insecticides. However, pendimethalin and the multiherbicide pesticides were moderately toxic to *T. vernalis.* All of the insecticides applied to cores increased the mortality of adult *T. vernalis* with the exception of halofenozide. The effect of the duration of pesticide exposure was not investigated during the study, but rather wasps were exposed for the entire 48-h period. Brief exposure of wasps to pesticides, which may typify the normal field situation, could minimize some of the adverse effects that occurred in this laboratory study. A more rapid dissipation of pesticides in the field also would reduce the potential of adult *T. vernalis* receiving a toxic dose. Sublethal pesticide effects such as reduced fecundity or impaired searching behavior could further reduce *T. vernalis* value in Japanese beetle management and should be investigated in the future (Rogers and Potter 2003). Imidacloprid was the only insecticide tested with known systemic activity in plants. Systemic pesticides may have other exposure hazards that were not examined in our study. For example, parasitoids that fed on extrafloral nectaries of imidacloprid-treated cotton plants exhibited abnormal flight behavior (Stapel et al. 2000). The propensity of *T. vernalis* adults to feed on carbohydrates may increase their exposure risk if systemic insecticides contaminate these resources. In conclusion, the results of this study indicate halofenozide, oryzalin, and most of the fungicides tested had minimal impact on survival of *T. vernalis,* particularly the female wasps. Therefore, pesticide users should opt for these active ingredients if conservation of *T. vernalis* in turf and landscape is a goal.

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References Cited

Antonious, G. F., and J. C. Snyder. 1995. Pirimiphos-methyl residues and control of greenhouse whitefly (Homoptera: Aleyrodidae) on seven vegetables. J. Entomol. Sci. 30: 191–201.

Arnold, T. B., and D. A. Potter. 1987. Impact of a high-maintenance lawn-care program on nontarget invertebrates in Kentucky bluegrass turf. Environ. Entomol. 16: 100–105.

Bellows, T. S., Jr., J. G. Morse, and L. K. Gaston. 1993. Residual toxicity of pesticides used for lepidopteran insect control of citrus to *Aphytis melinus* DeBach (Hymenoptera: Aphelinidae). Can. Entomol. 125: 995–1001.

Bradley, J. R., Jr. 1999. Integrating new insecticide technologies in IPM, pp. 384–399. *In* G. G. Kennedy and T. B. Sutton [eds.], Proceedings of the Emerging Technologies for Integrated Pest Management. Concepts, Research, and Implementation, 8–10 March 1999, Raleigh, NC. APS Press, St. Paul, MN.

Braman, S. K., R. D. Oetting, and W. Florkowski. 1997. Assessment of pesticide use by commercial landscape maintenance and lawn care firms in Georgia. J. Entomol. Sci. 32: 403–411.

Chukwudebe, A. C., D. L. Cox, S. J. Palmer, L. A. Morneweck, L. D. Payne, D. M. Dunbar, and P. G. Wislocki. 1997. Toxicity of emamectin benzoate foliar dislodgeable residues to two beneficial insects. J. Agric. Food Chem. 45: 3689–3693.

Cowles, R. S., S. R. Alm, and M. G. Villani. 1999. Selective toxicity of halofenozide to exotic white grubs (Coleoptera: Scarabaeidae). J. Econ. Entomol. 92: 427–434.

Dhadialla, T. S., G. R. Carlson, and D. P. Le. 1998. New insecticides with ecdysteroidal and juvenile hormone activity. Annu. Rev. Entomol. 43: 545–569.

Elliott, R. H. 1988. Evaluation of insecticides for protection of wheat against damage by the wheat midge *Sitodiplosis mosellana* (Gehin) (Diptera: Cecidomyiidae). Can. Entomol. 120: 615–626.

[Extoxnet PIP] Extoxnet Pesticide Information Profiles. 2005. Extoxnet pesticide information profiles. (http://extoxnet.orst.edu/pips/ghindex.html).

Fleming,W. E. 1968. Biological control of the Japanese beetle. U.S. Dep. Agric. Tech. Bull. No. 1383. Washington, DC.

Fleming, W. E. 1972. Biology of the Japanese beetle. U.S. Dep. Agric. Tech. Bull. No. 1449. Washington, DC.

Fleming, W. E. 1976. Integrating control of the Japanese beetle–a historical review. U.S. Dep. Agric. Tech. Bull. No. 1545. Washington, DC.

Garber, M. P., and W. G. Hudson. 1996. Pest management in the United States greenhouse and nursery industry. Horttechnology 6: 216–221.

Gardner, T. R. 1938. Influence of feeding habits of *Tiphia vernalis* on the parasitization of the Japanese beetle. J. Econ. Entomol. 31: 204–207.

Gardner, T. R., and L. B. Parker. 1940. Investigations of the parasites of *Popillia japonica* and related Scarabaeidae in the Far East from 1929 to 1933, inclusive. U.S. Dep. Agric. Tech. Bull. No. 738. Washington, DC.

Gels, J. A., D. W. Held, and D. A. Potter. 2002. Hazards of insecticides to the bumble bees *Bombus impatiens* (Hymenoptera: Apidae) foraging on flowering white clover in turf. J. Econ. Entomol. 95: 722–728.

Harris, C. R. 1982. Factors influencing the toxicity of insecticides in soil, pp. 47–52. *In* H. D. Niemczyk and B. G. Joyner [eds.], Advances in turfgrass entomology. Hammer Graphics Inc., Piqua, OH.

King, J. L., and L. B. Parker. 1950. The spring *Tiphia,* an imported enemy of the Japanese beetle. U.S. Dep. Agric. Publ. E-799.

King, J. L., L. B. Parker, and H. J. Willard. 1951. Status of imported parasites of the Japanese beetle in 1950. U.S. Dep. Agric. Spec. Suppl. No. 5: 1–17.

Kunkel, B. A., D. W. Held, and D. A. Potter. 1999. Impact of halofenozide, imidacloprid, and bendiocarb on beneficial invertebrates and predatory activity in turfgrass. J. Econ. Entomol. 92: 922–930.

Lickfeldt, D. W., and B. E. Branham. 1995. Sorption of nonionic organic compounds by Kentucky bluegrass leaves and thatch. J. Environ. Qual. 24: 980–985.

MacKay, D., W.-Y. Shiu, and K.-C. Ma. 1997. Illustrated handbook of physical-chemical properties and environmental fate for organic chemicals, vol. 5. Lewis Publishers, New York.

Mannion, C. M., W. McLane, M. G. Klein, J. Moyseenko, J. B. Oliver, and D. Cowan. 2001. Management of early-instar Japanese beetle (Coleoptera: Scarabaeidae) in field-grown nursery crops. J. Econ. Entomol. 94: 1151–1161.

Mizell, R. F., III, and M. C. Sconyers. 1992. Toxicity of imidacloprid to selected arthropod predators in the laboratory. Fla. Entomol. 75: 277–280.

Montgomery, J. 1997. Agrochemicals desk reference. CRC Lewis Publishers, Boca Raton, FL.

Niemczyk, H. D., and H. R. Krueger. 1987. Persistence and mobility of isazofos in turfgrass thatch and soil. J. Econ. Entomol. 80: 950–952.

Oliver, J. B., C. M. Mannion, M. G. Klein, J. J. Moyseenko, and B. Bishop. 2005. Effect of insecticides on *Tiphia vernalis* (Hymenoptera: Tiphiidae) oviposition and survival of progeny to cocoon stage when parasitizing *Popillia japonica* (Coleoptera: Scarabaeidae) larvae. J. Econ. Entomol. 98: 694–703.

Potter, D. A., and D. W. Held. 2002. Biology and management of the Japanese beetle. Annu. Rev. Entomol. 47: 175–205.

Reding, M. E., and M. G. Klein. 2001. *Tiphia vernalis* (Hymenoptera: Tiphiidae) parasitizing oriental beetle, *Anomala orientalis* (Coleoptera: Scarabaeidae) in a nursery. Great Lakes Entomol. 34: 67–68.

Rogers, M. E., and D. A. Potter. 2003. Effects of spring imidacloprid application for white grub control on parasitism of Japanese beetle (Coleoptera: Scarabaeidae) by *Tiphia vernalis* (Hymenoptera: Tiphiidae). J. Econ. Entomol. 96: 1412–1419.

Rogers, M. E., and D. A. Potter. 2004a. Biology and conservation of *Tiphia* wasps, parasitoids of turf-infesting white grubs. Acta Hortic. 661: 505–510.

Rogers, M. E., and D. A. Potter. 2004b. Biology of *Tiphia pygidialis* (Hymenoptera: Tiphiidae), a parasitoid of masked chafer (Coleoptera: Scarabaeidae) grubs, with notes on the seasonal occurrence of *Tiphia vernalis* in Kentucky. Environ. Entomol. 33: 520–527.

Rogers, M. E., and D. A. Potter. 2004c. Potential for sugar sprays and flowering plants to increase parasitism of white grubs (Coleoptera: Scarabaeidae) by tiphiid wasps (Hymenoptera: Tiphiidae). Environ. Entomol. 33: 619–626.

SAS Institute. 1996. The SAS system for Windows, release 6.12. SAS Institute, Cary, NC.

Sears, M. K., and R. A. Chapman. 1979. Persistence and movement of four insecticides applied to turfgrass. J. Econ. Entomol. 72: 272–274.

Stapel, J. O., A. M. Cortesero, and W. J. Lewis. 2000. Disruptive sublethal effects of insecticides on biological control: altered foraging ability and life span of a parasitoid after feeding on extrafloral nectar of cotton treated with systemic insecticides. Biol. Control 17: 243–249.

Terry, L. A., D. A. Potter, and P. G. Spicer. 1993. Insecticides affect predatory arthropods and predation on Japanese beetle (Coleoptera: Scarabaeidae) eggs and fall armyworm (Lepidoptera: Noctuidae) pupae in turfgrass. J. Econ. Entomol. 86: 871–878.

Theiling, K. M., and B. A. Croft. 1988. Pesticide side-effects on arthropod natural enemies: a database summary. Agric. Ecosys. Environ. 21: 191–218.

Tooker, J. F., and L. M. Hanks. 2000. Flowering plant hosts of adult hymenopteran parasitoids of central Illinois. Ann. Entomol. Soc. Am. 93: 580–588.

[TOR] Turf and Ornamental Reference. 2005. Turf and ornamental reference for plant protection products, 14th ed. Vance Communication, New York.

[USEPA] U.S. Environmental Protection Agency. 2000. Chlorpyrifos revised risk assessment and agreement with registrants. U.S. EPA prevention, pesticides and toxic substances (7506C) factsheet. (http://www.epa.gov/pesticides/op/chlorpyrifos/agreement.pdf).

[USDA] U.S. Department of Agriculture. 2003. Code of Federal Regulations. Title 7, Chapter III, Part 301, Subpart Japanese beetle. (http://ceris.purdue.edu/napis/pests/jb/freg/cfrjb.html).

Vittum, P. J., M. G. Villani, and H. Tashiro. 1999. Turfgrass insects of the United States and Canada, 2nd ed. Cornell University Press, Ithaca, NY.

Watschke, T. L., P. H. Dernoeden, and D. J. Shetlar. 1994. Managing turfgrass pests. Lewis Publishers, Ann Arbor, MI.

[WSSA] Weed Science Society of America. 1994. Herbicide handbook, 7th ed., W. Ahrens [ed.], Champaign, IL.

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